Robust Fixed-Architecture Linear and Nonlinear Control

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by

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13. ABSTRACT ***(Maximum 200 Words)***

Controls research under this program has concentrated on the development of linear and nonlinear robust fixed-structure control for aerospace systems. Specifically, a unified robust nonlinear design framework was developed that provides significant extensions of state-of-the-art recursive backstepping nonlinear control methods to include notions of optimality, robustness, disturbance rejection, actuator constraints, and adaptation. Furthermore, a general nonlinear control design framework predicated on a hierarchical switching controller architecture was developed. The proposed framework provides a rigorous alternative to designing gain scheduled feedback controllers that guarantee global closed-loop system stability for nonlinear systems. The aforementioned nonlinear control design frameworks were applied to the control of thermoacoustic combustion instabilities and compressor aerodynamic instabilities involving rotating stall and surge in aeroengines.

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1.0 Introduction

1.1 Research Objectives

The ability of developing an integrated control-system design methodology for robust, high performance controllers satisfying multiple design criteria and real-world hardware constraints is imperative in light of the increasingly complex nature of engineering systems requiring controls such as advanced high performance tactical fighter aircraft, large flexible space structures, and variable-cycle gas turbine engines, to cite but a few examples. The increasingly stringent performance requirements required for controlling such modern engineering systems necessitates a trade-off between control law complexity and control law robustness. Hence, one of the predominant considerations of modern multivariable control theory is to develop a control law design framework for modern engineering systems that minimizes control law complexity subject to the achievement of a specified accuracy in the face of a specified level of modeling uncertainty. As part of this research program we developed a unified fixed-architecture linear and nonlinear controller synthesis framework to address the problem of control law complexity and control law robustness. In particular, we concentrated on robust control, fixed-architecture control, nonlinear control, adaptive control, and homotopy algorithm development. Application areas included vibration control of aerospace structures, active vibration absorber and isolation technology, flight control, and control of combustion and propulsion of jet engines.

1.2 Overview of Research

Controls research by the Principal Investigator has concentrated on linear and nonlinear robust control with applications to aerospace systems [I.1-I.60, II.1-II.64]. In particular, the fixed-structure controller synthesis framework was extended to include multiobjective performance considerations involving mixed-norm H_2/L_1 and L_1/H_∞ designs, state constraints, decentralized robust controller architectures, stable stabilization, non-fragile controllers, time delays, parametric robustness with fixed-structure multipliers, parametric robustness without multipliers, sampled-data robustness in the delta-domain, actuator amplitude and rate saturation constraints, and optimal H_2 controllers with relative degree two. Furthermore, a robust nonlinear controller synthesis framework was developed using a modified Hamilton-Jacobi-Bellman framework to obtain robust globally stabilizing disturbance rejection controllers for nonlinear continuous-time and discrete-time systems. In addition, an inverse optimal adaptive control-system design framework for nonlinear uncertain systems with exogenous L_2 disturbances is developed. Furthermore, a nonlinear control design framework predicated on a hierarchical switching controller architecture was developed. The proposed framework provides a rigorous alternative to designing gain scheduled feedback controllers that guarantee global closed-loop system stability for general nonlinear systems. The aforementioned design frameworks were applied to the control of thermoacoustic combustion instabilities and compressor aerodynamic instabilities involving rotating stall and surge in axial and centrifugal jet engine compression systems.

1.3 Goals of this Report

The main goal of this report is to summarize the progress achieved under the program during the past three years. Since most of the technical results appeared or will soon appear in over 120 archival journal and conference publications, we shall only summarize these results and remark on their significance and interrelationship.

2.0 Description of Work Accomplished

The following research accomplishments have been completed over the past three years.

2.1 Nonlinear System Stabilization via Hierarchical Switching Control

Since all physical systems are inherently nonlinear with system nonlinearities arising from numerous sources including, for example, friction (eg., Coulomb, hysteresis), gyroscopic effects (eg., rotational motion), kinematic effects (eg., backlash), input constraints (eg., saturation, deadband), and geometric constraints, plant nonlinearities must be accounted for in the control-system design process. However, since nonlinear systems can exhibit multiple equilibria, limit cycles, bifurcations, jump resonance phenomena, and chaos, general nonlinear system stabilization is notoriously hard and remains an open problem. Control system designers have usually resorted to Lyapunov methods in order to obtain stabilizing controllers for nonlinear systems. In particular, for smooth feedback, Lyapunov-based methods were inspired by Jurdjevic and Quinn who give sufficient conditions for smooth stabilization based on the ability of constructing a Lyapunov function for the closed-loop system. Unfortunately, however, there does not exist a unified procedure for finding a Lyapunov function candidate that will stabilize the closed-loop system for general nonlinear systems.

If the operating range of the control system is small and if the system nonlinearities are smooth, then the control system can be locally approximated by a linearized system about a given operating condition and linear multivariable control theory can be used to maintain local stability and performance. However, in high performance aerospace engineering applications such as advanced tactical fighter aircraft and variable-cycle gas turbine aeroengines, the locally approximated linearized system does not cover the operating range of the system dynamics. In this case, gain scheduled controllers can be designed over several fixed operating points covering the system operating range and controller gains interpolated over this range. However, due to approximation linearization errors and neglected operating point transitions, the resulting gain scheduled system does not have any guarantees of performance or stability. Even though stability properties of gain scheduled controllers are analyzed in the literature and stability guarantees are provided for plant output scheduling, a *design* framework for gain scheduling control guaranteeing system stability over an operating range of the nonlinear plant dynamics has not been addressed in the literature.

In an attempt to develop a design framework for gain scheduling control, linear parameter-varying system theory has been developed. Since gain scheduling control involves a linear parameter-dependent plant, linear parameter-varying methods for gain scheduling seem natural. However, even though this is indeed the case for linear dynamical systems involving exogenous parameters, this is not the case for nonlinear dynamical systems. This is due to the fact that a nonlinear system cannot be represented as a true linear parameter-varying system since the varying system parameters are endogenous, that is, functions of the system state. Hence, stability and performance guarantees of linear parameter-varying systems do *not* extend to the nonlinear system. Of course, in the case where the magnitude and rate of the endogenous parameters are constrained such that the linear parameter-varying system *hopefully* behaves closely to the actual nonlinear system, then *a posteriori* stable controllers can be designed. However, in the case of unexpectedly large amplitude uncertain exogenous disturbances and/or system parametric uncertainty, *a priori* assumptions on magnitude and rate constraints on endogenous parameters are unverifiable.

In this research [I.51, I.53, II.35, II.47, II.52, II.64] a nonlinear control design framework predicated on a hierarchical switching controller architecture parameterized over a set of moving system equilibria is developed. Specifically, using *equilibria-dependent Lyapunov functions* or, instantaneous (with respect to a given parameterized equilibrium manifold) Lyapunov functions, a hierarchical nonlinear control strategy is developed that stabilizes a given nonlinear system using a supervisory switching controller that coordinates lower-level stabilizing subcontrollers (see Figure 1). Each subcontroller can be nonlinear and thus local set point designs can be nonlinear. Furthermore, for each parameterized equilibrium manifold, the collection of subcontrollers provide guaranteed domains of attraction with nonempty intersections that cover the region of operation of the nonlinear system in the state space. The hierarchical switching nonlinear controller architecture is developed based on a *generalized* lower semicontinuous Lyapunov function obtained by minimizing a potential function, associated with each domain of attraction, over a given switching set induced by the parameterized system equilibria. The switching set specifies the subcontroller to be activated at the point of switching, which occurs within the intersections of the domains of attraction. The hierarchical switching nonlinear controller guarantees that the generalized Lyapunov function is nonincreasing along the closed-loop system trajectories with strictly decreasing values at the switching points, establishing asymptotic stability (see Figure 2). In the case where one of the parameterized system equilibrium points is globally asymptotically stable, the proposed nonlinear stabilization framework guarantees global asymptotic stability of any given system equilibrium on the parameterized system equilibrium branch. Furthermore, since the proposed switching nonlinear control strategy is predicted on a generalized

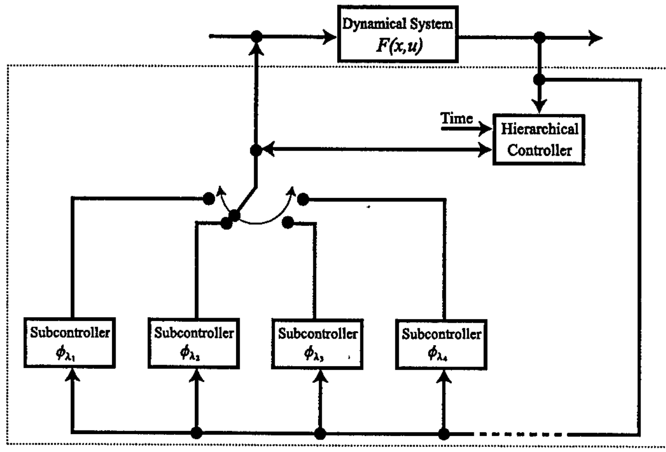


Figure 1: Hierarchical control structure

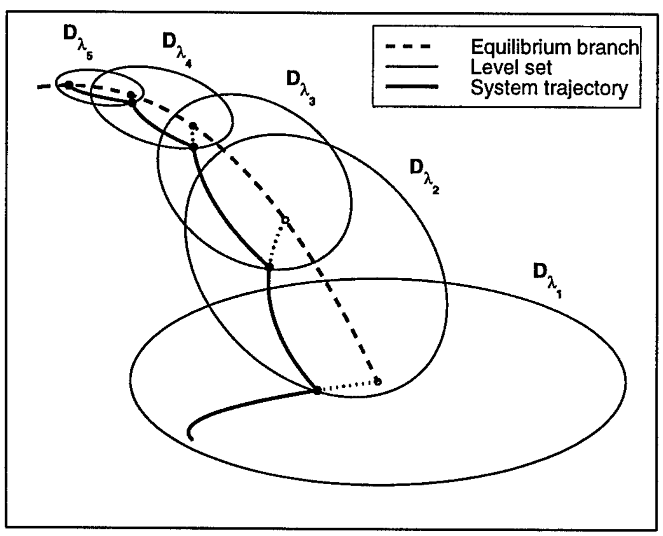


Figure 2: Hierarchical switching control stategy

Lyapunov function framework with strictly decreasing values at the switching points, the possibility of a sliding mode is precluded. Hence, the proposed nonlinear stabilization framework avoids the undesirable effects of high-speed switching onto an invariant sliding manifold which is one of the main limitations of variable structure controllers. Finally, we note that the present framework provides a rigorous alternative to designing gain scheduled controllers for general nonlinear systems by explicitly capturing plant nonlinearities and quantifying the notion of slow-varying system parameters which place fundamental limitations on achievable performance of gain scheduling controllers.

2.2 Generalized Lyapunov and Invariant Set Theorems for Nonlinear Dynamical Systems

Most Lyapunov stability and invariant set theorems presented in the literature require that the Lyapunov function candidate for a nonlinear dynamical system be a C^1 function with a negative-definite derivative. This is due to the fact that the majority of the dynamical systems considered are systems possessing continuous motions and hence Lyapunov theorems provide stability conditions that do not require knowledge of the system trajectories. However, in light of the increasingly complex nature of dynamical systems such as biological systems, hybrid systems, sampled-data systems, discrete-event systems, gain scheduled systems, constrained mechanical systems, and impulsive systems, system discontinuities as well as discontinuous motions arise naturally. In the case of discontinuous motions, standard Lyapunov and invariant set theorems are in general not applicable. Alternatively, in the case of discontinuous system dynamics with continuous motions standard Lyapunov theory is applicable, however, it might be simpler to construct discontinuous "Lyapunov" functions to establish system stability. For example, in gain scheduling control it is not uncommon to use several different controllers designed over several fixed operating points covering the system's operating range and to switch between them over this range. Even though for each operating range one can construct a C^1 Lyapunov function, to show closed-loop system stability over the whole system operating envelope for a given switching control strategy, a *generalized* Lyapunov function involving combinations of the Lyapunov functions for each operating range can be constructed. However, in this case, it can be shown that the generalized Lyapunov function is non-smooth and non-continuous.

In this research [I.56, II.52] we develop generalized Lyapunov and invariant set theorems for nonlinear dynamical systems wherein all regularity assumptions on the Lyapunov function and the system dynamics are removed. In particular, local and global stability theorems are presented using generalized Lyapunov functions that are lower semicontinuous. Furthermore, generalized invariant set theorems are derived wherein system trajectories converge to a union of largest invariant sets contained in intersections over finite intervals of the closure of generalized Lyapunov level surfaces. In the case where the generalized Lyapunov function is taken to be a C^1 function, our results collapse to the standard Lyapunov stability and invariant set theorems.

2.3 Generalized Inverse Optimal Nonlinear Control

In this research [I.55, II.32] we derive guaranteed gain, sector, and disk margins for nonlinear optimal and inverse optimal regulators that minimize a nonlinear-nonquadratic performance criterion involving cross-weighting terms. Specifically, sufficient conditions that guarantee gain, sector, and disk margins are given in terms of the state, control, and cross-weighting nonlinear-nonquadratic weighting functions. The proposed results provide a generalization of the "meaningful" inverse optimal nonlinear regulator stability margins as well as the classical linear-quadratic optimal regulator gain and phase margins. Discrete-time extensions of these results as well as discrete-time control Lyapunov functions and inverse optimality are developed [I.54, II.45].

2.4 Fixed-Structure Nonlinear Optimal Output Feedback Control

Although the theory for designing linear output feedback controllers is quite mature, nonlinear output feedback controller synthesis remains relatively undeveloped. In numerous real world applications system nonlinearities such as saturation, relay, deadzone, quantization, geometric, and material nonlinearities require nonlinear output feedback controllers. Furthermore, for linear plants with parametric uncertainty and nonquadratic performance criteria, nonlinear controllers exist that generate superior performance over the best linear controller. In this research [II.53] we develop a preliminary fixed-structure controller synthesis framework for nonlinear control. The motivation for fixed-structure nonlinear control theory is to address controller synthesis within a class of candidate nonlinear feedback controller structures. Specifically, Lyapunov functions are used to provide a controller synthesis framework by assuring global or regional asymptotic stability for an *a priori* fixed class of nonlinear feedback controllers. A specific controller within this class can now be chosen to optimize a given performance functional. Thus, this provides a constructive framework where Lyapunov theory is used to guarantee global or regional asymptotic stability over a class of nonlinear feedback controllers while optimization is performed over the free controller gains so as to minimize a specific performance functional.

The first stage of this approach is concerned with the synthesis of fixed-structure, state feedback and output feedback, nonlinear control laws and corresponding fixed-structure Lyapunov functions that increase the domain of attraction of a given nonlinear system about an equilibrium point of the system. The reason for explicitly considering increasing the domain of attraction, as opposed to ensuring global asymptotic stability, is that in practice it may be sufficient to have a controller with an adequately large domain of attraction. Furthermore, for some nonlinear systems global asymptotic stability may not be achievable via nonlinear output feedback (or even state feedback).

The second stage of this approach is concerned with finding a fixed-structure nonlinear control law that optimizes an *a priori* chosen performance functional. It is assumed that the first stage, described above, results in a set of (regionally) stabilizing control laws. This second stage then finds a member of this set which optimizes a particular cost function. It is important to note that our nonlinear controllers are *not* predicated on an inverse optimal control problem wherein, in order to avoid the complexity in solving the Hamilton-Jacobi-Bellman equation, a *derived* cost functional as opposed to a *given* cost functional is minimized. Even though inverse optimal controllers may possess indirect robustness guarantees to multiplicative input uncertainty, the performance of the resulting controllers can be arbitrarily poor when compared to the optimal performance as measured by a designer specified cost functional. Furthermore, since such controllers are predicated on Hamilton-Jacobi-Bellman theory they are limited to full-state feedback control.

2.5 Globally Stabilizing Control for Centrifugal Compressors

While the literature on modeling and control of compression systems predominantly focuses on axial flow compression systems, the research literature on centrifugal flow compression systems is rather limited in comparison. In contrast to axial flow compression systems involving the aerodynamic instabilities of rotating stall and surge, surge and deep surge is the predominant aerodynamic instability arising in centrifugal compression systems. Surge is a one-dimensional axisymmetric global compression system oscillation which involves radial flow oscillations and in some case even radial flow reversal (deep surge) which can damage engine components.

In this research [I.36, II.36, II.46] we address the problem of nonlinear stabilization for centrifugal compression systems. First, we develop a three-state lumped parameter model for surge in centrifugal flow compression systems that is accessible to control-system designers requiring state space models for modern nonlinear control. Specifically, pressure and mass flow compression system dynamics are developed using principles of conservation of mass and momentum. Furthermore, in order to account for the influence of speed transients on the compression surge dynamics, turbocharger spool dynamics are also considered.

Next, using the hierarchical switching control framework discussed in Section 2.1, we develop a globally stabilizing control law for the lumped parameter centrifugal compressor surge model. In particular, using the backstepping control framework, a Lyapunov function for the closed-loop system is constructed leading to a nonlinear control architecture involving throttle and compressor torque regulation. The proposed nonlinear controller is applied to the developed centrifugal compressor surge model with spool dynamics. Figure 3 shows the pressure-flow (ψ-ϕ) phase portrait of the state trajectories when the controlled and uncontrolled compression system is taken from an operating speed of 20,000 rpm to 25,000 rpm. Finally, actuator amplitude and rate saturation constraints are also addressed [I.36, II.46].

2.6 Robust Stabilization of Axial Flow Compressors with Uncertain Pressure-Flow Maps

In this research [I.40, II.22] we develop globally robustly stabilizing controllers for rotating stall and surge in multi-mode axial flow compressor models with uncertain pressure-flow compressor performance characteristic maps. Specifically, using Lyapunov stability theory, a novel nonlinear globally robustly stabilizing control law based on equilibria-dependent Lyapunov functions with converging domains of attraction is developed. The locus of the equilibrium points on which the equilibria-dependent Lyapunov functions are predicated is characterized by the axisymmetric stable pressure-flow equilibrium branch of the nominal compression system.

2.7 Fixed-Order Dynamic Compensation for Linear Systems with Actuator Amplitude and Rate Saturation Constraints

In this research [I.48, II.42, II.50] we develop fixed-order (i.e., full- and reduced-order) controllers for linear systems with actuator amplitude and rate saturation constraints. The problem is formulated as a multiobjective problem involving a convex combination of an L_1 norm and the H_2 norm to capture actuator saturation constraints and closed-loop system performance in the face of exogenous white noise disturbances. The L_1 convolution operator norm considered is induced

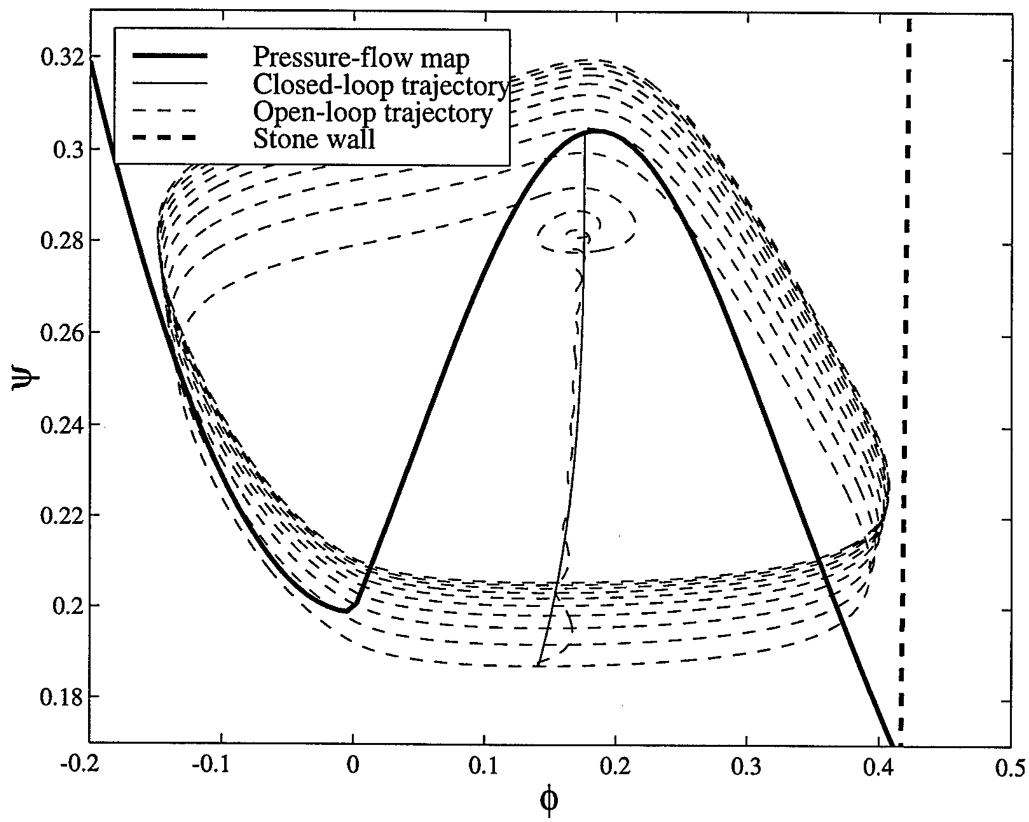


Figure 3: Controlled and uncontrolled phase portrait of pressure-flow state trajectories from 20,000 rpm to 25,000 rpm

by bounded amplitude persistent L_∞ disturbances and L_∞ performance variables involving the actuator amplitude and rate signals. Hence, the peak point-wise-in-time actuator amplitude and actuator rate excursion is guaranteed to be less than the product of the L_1 convolution operator norm and the L_∞ disturbance amplitude bound. Application of the proposed framework to the design of multivariable saturation controllers for high-performance fighter aircrafts is demonstrated. An alternative approach to actuator amplitude and rate saturation control is also presented in [I.41, II.43] using absolute stabilization notions.

2.8 Actuator Amplitude Saturation Control for Systems with Exogenous Disturbances

In this research [I.49, II.34] we develop fixed-order (i.e., full- and reduced-order) controllers for systems with actuator amplitude constraints and exogenous bounded energy L_2 disturbances. The actuator amplitude saturation and disturbance rejection constraints are embedded within an optimization problem by constructing a Riccati equation whose solution guarantees closed-loop global asymptotic stability in the face of sector bounded input nonlinearities and nonexpansivity (gain boundedness) of the input-output system energy.

2.9 Optimal H_2 Synthesis of Controllers with Relative Degree Two

It is well known that modern multivariable control design frameworks such as H_2 and H_∞ control yield dynamic compensators with relative degree zero or one. Hence, the structure of the dynamic feedback controller is such that the measured system output appears explicitly in the control signal or the measured system output appears explicitly in the control rate signal. In the single-input/single-output system case, the resulting controller transfer function is nonstrictly proper or strictly proper with relative degree one. In this case, the Bode plot of the controller transfer function rolls off at 20 dB per decade. Alternatively, for relative degree r controllers, the Bode plot of the compensator has a high frequency roll-off of $20r$ dB per decade.

High frequency roll-off is particularly useful when the system under consideration is a lightly damped flexible structure. Since flexible structure models are by necessity truncated to a finite number of modes, it is desirable for the frequency response to roll off as quickly as possible after the gain crossover frequency so the unmodelled high frequency systems dynamics are not excited by the controller dynamics. This research [I.30, II.31] considers fixed-structure H_2-optimal relative degree two controller synthesis. The problem is presented in a decentralized static output feedback framework developed for fixed-order (i.e., full- and reduced-order) dynamic controller synthesis. A quasi-Newton/contribution algorithm is used to compute solutions to the necessary conditions.

2.10 Stabilization of Linear Systems with Simultaneous State, Actuation, and Measurement Delays

This research [I.38, II.37] considers the problem of stabilizing continuous-time linear systems with time delays. Specifically, a fixed-order (i.e., full- and reduced-order) dynamic compensation problem is addressed for systems with simultaneous state, input, and output delays. The principal result involves sufficient conditions for characterizing fixed-order dynamic controllers for delay systems via a system of modified coupled Riccati equations. The controllers obtained are delay independent and hence apply to systems with arbitrary unknown delay.

2.11 Inverse Optimal Adaptive Control for Nonlinear Uncertain Systems with Exogenous Disturbances

A Lyapunov-based optimal adaptive control-system design problem for nonlinear uncertain systems with exogenous L_2 disturbances is considered [I.37, II.27]. Specifically, an inverse optimal adaptive nonlinear control framework is developed to explicitly characterize globally stabilizing disturbance rejection adaptive controllers that minimize a nonlinear-nonquadratic performance functional for nonlinear cascade and block cascade systems with parametric uncertainty. It is shown that the adaptive Lyapunov function guaranteeing closed-loop stability is a solution to the Hamilton-Jacobi-Isaacs equation for the controlled system and thus guarantees both optimality and robust stability. Additionally, the adaptive Lyapunov function is dissipative with respect to a weighted input-output energy supply rate guaranteeing closed-loop disturbance rejection. For special integrand structures of the performance functionals considered, the proposed adaptive controllers additionally guarantee robustness to multiplicative input uncertainty. In the case of linear-quadratic control it is shown that the operations of parameter estimation and controller design are coupled illustrating the breakdown of the certainty equivalence principle for the optimal adaptive control problem. Finally, the proposed framework is used to design adaptive controllers for jet engine compression systems with uncertain compressor performance pressure-flow maps. Figures 4, 5, and 6 show the squared stalled cell amplitude, compressor flow rate, pressure rise, and control effort of a typical compressor controlled by the optimal adaptive controller [I.37], a nonlinear guaranteed cost controller developed under this research effort [I.45], the standard Kokotovic adaptive backstepping controller, the bifurcation-based Nett controller, and the bifurcation-based Abed controller. Figure 7 gives a comparison of the level of parameter

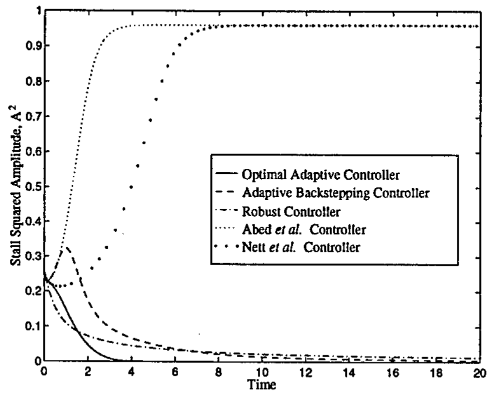


Figure 4: Squared stall cell amplitude versus time

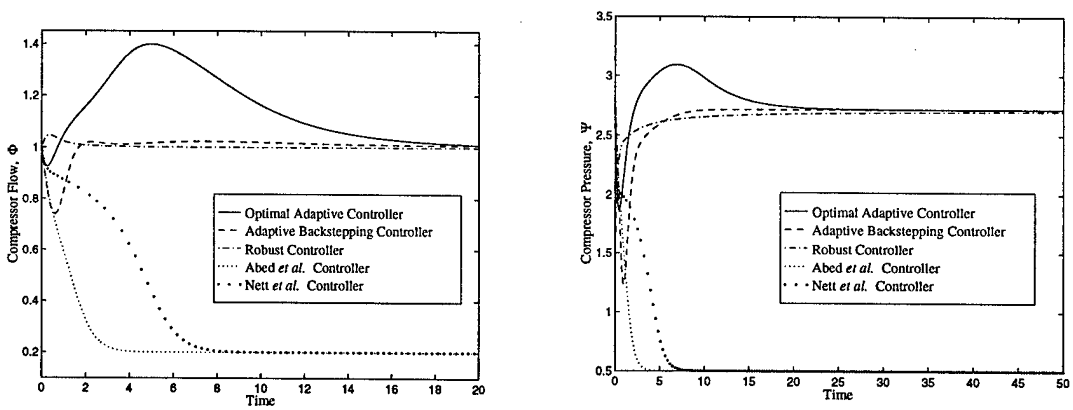
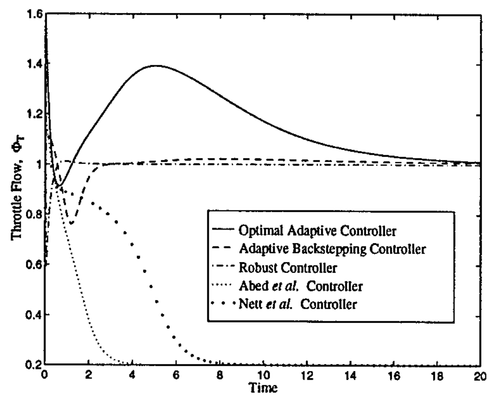


Figure 5: Compressor flow and pressure versus time



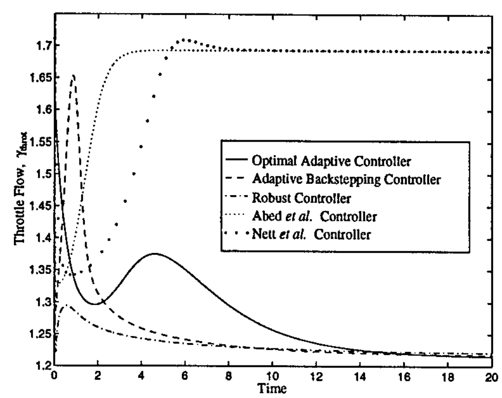


Figure 6: Control effort versus time

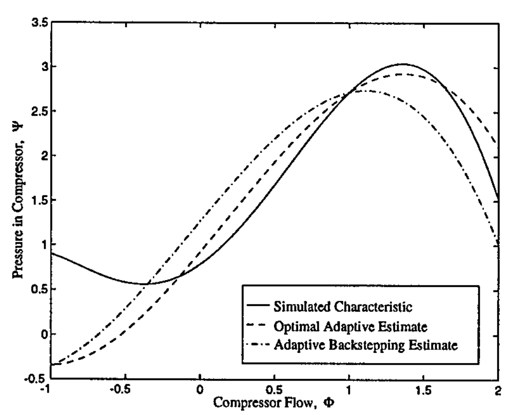


Figure 7: Actual and identified compressor characteristic maps

convergence in terms of the compressor characteristic maps identified by the optimal adaptive controller and the adaptive backstepping controller of Kokotovic.

2.12 Optimal Nonlinear Robust Control for Nonlinear Systems with Parametric Uncertainty

In this research [I.45, II.4] we develop an optimality-based robust control framework for uncertain systems with structured parametric uncertainty. Specifically, using an optimal nonlinear robust control framework we develop a family of globally stabilizing robust backstepping controllers parameterized by the cost functional that is minimized. Furthermore, it is shown that the robust Lyapunov function guaranteeing closed-loop stability over a prescribed range of structured system parametric uncertainty is a solution to the steady-state Hamilton-Jacobi-Bellman equation for the controlled system and thus guarantees robust stability and robust performance. The results are then used to design robust controllers for jet engine compression systems with uncertain pressure-flow compressor characteristic performance maps.

2.13 Optimal Nonlinear Disturbance Rejection Control for Nonlinear Cascade Systems

In this research [I.11, II.5] we develop an optimality-based disturbance rejection control framework for nonlinear cascade systems with bounded energy (square-integrable) L_2 disturbances. Specifically, using a nonlinear-nonquadratic disturbance rejection optimal control framework we develop a family of globally stabilizing generalized backstepping controllers parameterized by the cost functional that is minimized. Furthermore, it is shown that the Lyapunov function guaranteeing closed-loop stability is a solution to the steady-state Hamilton-Jacobi-Isaacs equation for the controlled system and thus guarantees both optimality and stability. In addition, the resulting optimal controller guarantees that the closed-loop system is nonexpansive (gain bounded). The proposed framework is applied to the control of rotating stall and surge in jet engine compression systems.

2.14 Nonlinear Controllers for Nonlinear Systems with Input Nonlinearities

In this research [I.29, II.25] we develop an optimality-based *globally* stabilizing controller framework that addresses the problem of multivariable nonlinear systems subject to plant input sector bounded nonlinearities while accounting for robust stability and performance over the class of allowable nonlinearities. This framework is directly applicable to nonlinear systems with saturation controls. Specifically, a robust nonlinear control problem is transformed into an optimal control problem by modifying a nonlinear-nonquadratic cost functional to account for nonlinear system uncertainty. Furthermore, it was shown that the robust Lyapunov function guaranteeing closed-loop stability is a solution to the steady-state Hamilton-Jacobi-Bellman equation for the controlled nominal system. By re-interpreting system input nonlinearities as system uncertainty, the results developed in [I.45] are directly applicable to nonlinear systems with input nonlinearities.

2.15 Nonlinear Robust Disturbance Rejection Controllers for Rotating Stall and Surge in Axial Flow Compressors

The desire for developing an integrated control system-design methodology for advanced propulsion systems has led to significant activity in modeling and control of flow compression systems in recent years. However, unavoidable discrepancies between compression system models and real-world compression systems can result in degradation of control-system performance including instability. In particular, jet engine compression systems with uncertain performance pressure-flow characteristic maps can severely limit jet engine compression system performance by inducing the compressor aerodynamic instabilities of rotating stall and surge. Rotating stall is an inherently two-dimensional local compression system oscillation which is characterized by regions of flow that rotate at a fraction of the compressor rotor speed while surge is a one-dimensional axisymmetric global compression system oscillation which involves axial flow oscillations and in some cases even axial flow reversal which can damage engine components and cause flameout to occur.

In this research [I.28, II.23] we develop globally stabilizing robust/disturbance rejection controllers for rotating stall and surge in axial flow compressors with uncertain compressor performance pressure-flow characteristic maps. Specifically, using the nonlinear-nonquadratic disturbance rejection optimal control framework for systems with bounded energy (square-integrable) L_2 disturbances developed in [I.11] and the nonlinear-nonquadratic robust optimal control framework for systems with nonlinear parametric uncertainty developed in [I.45], a *family* of globally robustly stabilizing controllers for jet engine compression systems is developed. The proposed controllers are compared with the locally stabilizing bifurcation-based controllers of Abed and Nett and the recursive backstepping controllers of Kokotovic.

2.16 Globally Stabilizing Controllers for Multi-Mode Axial Flow Compressor Models via Equilibria-Dependent Lyapunov Functions

In this research [I.25, II.7] we develop a self-contained first principles derivation of a multi-mode model for rotating stall and surge in axial flow compression systems that is accessible to control-system designers requiring state space models for modern nonlinear control design. Specifically, the formulation is based on a generalized multi-mode expansion of the disturbance velocity potential in the flow field which accounts for the coupling between higher-order system harmonics and the pressure rise and mean flow through the compressor. Using the multi-mode state space model we show that the globally stabilizing backstepping controller developed by Kokotovic and co-workers predicated on the one-mode Moore-Greitzer model drives the compression system to a stalled condition in the case where two-modes are included in the model. This clearly indicates that the higher-order disturbance velocity potential harmonics strongly interact with the first harmonic during stall inception and must be accounted for in the control design process to achieve control performance objectives.

Using Lyapunov stability theory, a novel nonlinear globally stabilizing control law for the multi-mode axial flow compressor models based on equilibria-dependent Lyapunov functions with converging domains of attraction is developed [I.25, II.20]. The locus of equilibrium points on which the equilibria-dependent, or instantaneous, Lyapunov functions are predicated are characterized by the axisymmetric equilibria of the compression system. The proposed nonlinear controller guarantees global stability for an arbitrary number of modes in the compression system.

2.17 Optimal Discrete-Time Control for Nonlinear Cascade Systems

Since most physical processes evolve naturally in continuous time, it is not surprising that the bulk of nonlinear control theory has been developed for continuous-time systems. Nevertheless, it is the overwhelming trend to implement controllers digitally. Despite this fact the development of nonlinear control theory for discrete-time systems has lagged its continuous-time counterpart. This is in part due to the fact that concepts such as zero dynamics, normal forms, and minimum phase are much more intricate for discrete-time systems. In this research [I.14, II.12] we develop an optimality-based framework for designing controllers for discrete-time nonlinear cascade systems. Specifically, using a nonlinear-nonquadratic optimal control framework we develop a family of globally stabilizing backstepping-type controllers parameterized by the cost functional that is minimized. Furthermore, it is shown that the control Lyapunov function guaranteeing closed-loop stability is a solution to the steady-state Bellman equation for the controlled system and thus guarantees both optimality and stability.

2.18 Multiobjective L_1/H_∞ Controller Design for Systems with Frequency and Time Domain Constraints

In this research [I.52, II.41] we develop an optimal mixed-norm L_1/H_∞ and l_1/H_∞ controller synthesis framework for continuous-time and discrete-time systems. This multiobjective problem is treated by framing a convex combination of both L_1 (time domain worst-case peak amplitude response) and entropy (frequency domain worst-case H_∞ disturbance attenuation) performance measures. For flexibility in controller synthesis, we adopt the approach of fixed-structure controller design which allows consideration of arbitrary controller structures, including order, internal structure, and decentralization. Finally, using a quasi-Newton continuation algorithm, we demonstrate the effectiveness of the proposed mixed-norm L_1/H_∞ approach via several design examples including command following for a high-performance fighter aircraft.

2.19 Robust Resilient Controllers for Systems with Parametric Uncertainty and Controller Gain Variations

One of the fundamental problems in feedback control design is the ability of the control system to maintain stability and performance in the face of system uncertainties. To this end, elegant multivariable robust control design frameworks such as H_∞ control, L_1 control, and μ synthesis have been developed to address the robust stability and performance control problem. An implicit assumption inherent in these design frameworks is that the controller will be implemented exactly. In a recent paper by Keel and Bhattacharyya it was shown that even though such frameworks are robust with respect to system uncertainty, they are extremely fragile with respect to errors in the controller coefficients. In this research [I.50, II.28, II.39, II.49], we extend the fixed-structure controller synthesis approach to develop non-fragile or *resilient* controllers to controller gain variations and system parametric uncertainty.

2.20 Robustness Analysis in the Delta-Domain Using Fixed-Structure Multipliers

Developments in mixed (i.e., real and complex) structured singular value theory and the associated multiplier-based analysis results have greatly reduced the conservatism in the analysis of systems with mixed uncertainty. However, most of these advances have focused on continuous-time systems although in practice it is more natural to consider discrete-time systems. Hence, this research [I.46, II.29] presents robustness tests for the analysis of discrete-time systems. To avoid the inherent numerical ill-conditioning resulting from the use of the standard forward-shift representation and to help unify the continuous-time and discrete-time robustness theories, the developments are based on the delta-domain representation of a discrete-time system. After presenting a general frequency-domain robustness test, LMI state space tests are developed. The results are then specialized to delta-domain Popov-type multipliers and illustrated with several numerical examples.

2.21 Fixed-Architecture Controllers for Systems with Amplitude Saturation and Time Delay

In this research [II.38] we consider the problem of stabilizing dynamic systems in the face of amplitude saturation and time delay. Specifically, a fixed-order (i.e., full- and reduced-order) dynamic output feedback framework is developed for systems with sector bounded input nonlinearities and simultaneous state, input, and output delays. Discrete-time extensions are presented in [I.20].

2.22 Robust Stabilization for Continuous-Time Systems with Slowly Time-Varying Uncertain Real Parameters

In this research [I.16] we construct a new class of parameter-dependent Lyapunov functions to guarantee robust stability in the presence of time-varying rate-restricted plant uncertainty. Extensions to a class of time-varying nonlinear uncertainty that generalizes the multivariable Popov criterion are also considered. These results are then used for controller synthesis to address the problem of robust stabilization in the presence of slowly time-varying real parameters. The results are directly applicable to propulsion systems where uncertain system mass is being ejected from the system.

2.23 Stable H_2-Optimal Controller Synthesis

This research [I.44, II.9] considers fixed-structure stable H_2-optimal controller synthesis using a Pareto optimization technique. The problem is presented in a decentralized static output feedback framework developed for fixed-structure dynamic controller synthesis. A quasi-Newton/continuation algorithm is developed to compute solutions to the necessary conditions. The approach is demonstrated on several flexible structure examples. The results are then compared with other methods of stable compensator synthesis.

2.24 Active Vibration Isolation of Multi-Degree of Freedom Systems

One of the principal objectives of vibration isolators is to either isolate sensitive equipment from a vibrating structure or to isolate the structure from an uncertain exogenous disturbance source. Vibration suppression between a base body (containing the disturbance source) and an isolated body can be achieved by intrastructural damping approaches or active isolation. In intrastructural damping approaches to isolation a damping energy dissipation mechanism is inserted between the two bodies which can be implemented passively (e.g., viscoelastic dampers) or actively (e.g., piezoelectric actuators). However, since such isolation members transmit vibrational energy in the process of dissipating energy they simply reduce the resonance peaks of the isolated body response but do not reduce the broadband nonresonant response. Alternatively, active isolation approaches which combine intrastructural actuation and inertial sensing can prevent vibration transmission into the isolated body and hence suppress the resonant and nonresonant responses over a broad frequency band. In this research [I.32, II.18], a dynamic observer-based active isolator is proposed that guarantees closed-loop asymptotic stability and disturbance decoupling between the vibrating structure and isolated structure. The proposed active isolator is applied to a uniaxial vibrational system and compared to optimal linear-quadratic designs.

2.25 Resetting Virtual Absorbers for Vibration Control

In vibration control problems, if a plant is at a high energy level, and a physical absorber at a low energy level is attached to it, then energy will generally tend to flow from the plant into the absorber, decreasing the plant energy and increasing the absorber energy. Conversely, if the plant is at a low energy level and an attached absorber is at a high energy level, then energy will tend to flow from the absorber into the plant. This behavior is also exhibited by a plant with an attached virtual absorber, although in this case emulated energy, and not physical energy, is accumulated by the virtual absorber. Nonetheless, energy can flow from a virtual absorber to the plant, since a virtual absorber with emulated energy can generate real, physical energy to effect the required energy flow. Therefore, when using a virtual absorber, it may be advantageous to detect when the position and velocity states of the emulated absorber represent a high emulated energy level, and then *reset* these states to remove the emulated energy so that the emulated energy is not returned to the plant. A virtual absorber whose states are reset is called a *resetting virtual absorber*. In this research [I.31, II.14] a general framework for analyzing resetting virtual absorbers is given, and stability of the closed-loop system is analyzed. Special cases of resetting virtual absorbers, called the virtual trap-door absorber and the virtual one-way absorber, are described and several designs are carried out to demonstrate the utility of the proposed approach.

2.26 Robust Nonlinear Feedback Control with Nonquadratic Performance Criteria

In this work [I.18] we develop a unified framework to address the problem of optimal nonlinear robust control. Specifically, we transform a given robust control problem into an optimal control problem by properly modifying the cost functional to account for the system uncertainty. As a consequence, the resulting solution to the modified optimal control problem guarantees robust stability and performance for a class of nonlinear uncertain systems. The overall framework generalizes the classical Hamilton-Jacobi-Bellman conditions to address the design of robust optimal controllers for uncertain nonlinear systems.

In order to address the problem of optimal nonlinear-nonquadratic robust control for systems with nonlinear time-invariant real parameter uncertainty, we extended the framework in [I.18] to robust nonlinear-nonquadratic feedback control using a parameter-dependent Lyapunov function approach [I.3, II.1]. Specifically, robust stability of the closed-loop nonlinear system is guaranteed by means of a parameter-dependent Lyapunov function composed of a fixed (parameter-independent) and variable (parameter-dependent) part. The fixed part of the Lyapunov function can clearly be seen to be the solution to the steady-state Hamilton-Jacobi-Bellman equation for the nominal system. The overall framework generalizes the classical Hamilton-Jacobi-Bellman conditions to address the design of robust optimal controllers for uncertain nonlinear systems via parameter-dependent Lyapunov functions and provides the foundation for extending robust linear-quadratic controller synthesis to robust nonlinear-nonquadratic problems.

2.27 Optimal Nonlinear-Nonquadratic Feedback Control with Bounded Energy and Amplitude Disturbances

In this research [I.21, I.35, II.6, II.44] we develop an optimality-based framework to address the problem of nonlinear-nonquadratic control for disturbance rejection of nonlinear systems with bounded uncertain exogenous disturbances. Specifically, using nonlinear dissipation theory with appropriate storage functions and supply rates we transform the nonlinear disturbance rejection problem into an optimal control problem by modifying a nonlinear-nonquadratic cost functional to account for the exogenous disturbances. As a consequence, the resulting solution to the modified optimal control problem guarantees disturbance rejection for nonlinear systems with bounded input disturbances. Furthermore, it is shown that the Lyapunov function guaranteeing closed-loop stability is a solution to the steady-state Hamilton-Jacobi-Bellman equation for the controlled system. The overall framework generalizes the Hamilton-Jacobi-Bellman conditions to address the design of optimal controllers for nonlinear systems with exogenous disturbances. It is shown that our results extend the recent nonlinear equivalents of H_∞ analysis and synthesis to include optimality considerations with nonlinear-nonquadratic cost functionals.

2.28 A Unification Between Nonlinear-Nonquadratic Optimal Control and Integrator Backstepping

In this research [I.22, II.26] we develop an optimality-based framework for backstepping controllers for nonlinear systems. Specifically, using a nonlinear-nonquadratic optimal control framework we develop a family of globally stabilizing backstepping controllers parameterized by the cost functional that is minimized. Furthermore, it is shown that the Lyapunov function, obtained using backstepping procedures, guaranteeing closed-loop stability is a solution to the steady-state Hamilton-Jacobi-Bellman equation for the controlled system and thus guarantees both optimality and stability. The results are specialized to the cases of integrator backstepping and block backstepping for cascade systems with linear and nonlinear input subsystems. The proposed framework is applied to the control of rotating stall and surge in jet engines. Specifically, *optimal* backstepping controllers are designed that *globally* stabilize the closed-loop dynamics while minimizing a nonlinear-nonquadratic performance criterion. The framework yields optimal backstepping controllers that outperform standard backstepping controllers proposed by Kokotovic *et al.* and bifurcation-based controllers which are limited to local stability guarantees. Figures 8, 9, and 10 show the squared stall cell amplitude, compressor flow rate, pressure rise, and control effort of a typical axial compressor controlled by the optimal backstepping controller and a standard backstepping controller.

2.29 Nonlinear Controller Synthesis for Dissipative Systems

It is well known from thermodynamic principles that energy flows from a hot state to a cold state. It is less well known, however, that a similar phenomenon occurs in coupled multi-degree of freedom dynamic systems with modal energy mimicking the role of temperature. This energy flow concept in mechanical systems, known as Statistical Energy Analysis, has been used to analyze linear dynamic systems. In [I.13, II.11] we extend these ideas to analysis and synthesis of nonlinear feedback controllers. Specifically, by viewing the dynamic system and the controller as

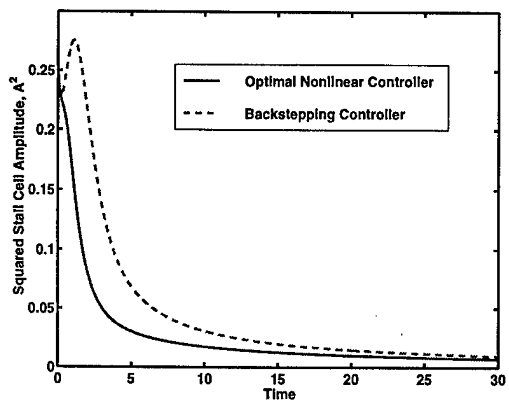


Figure 8: Squared stall cell amplitude vs time

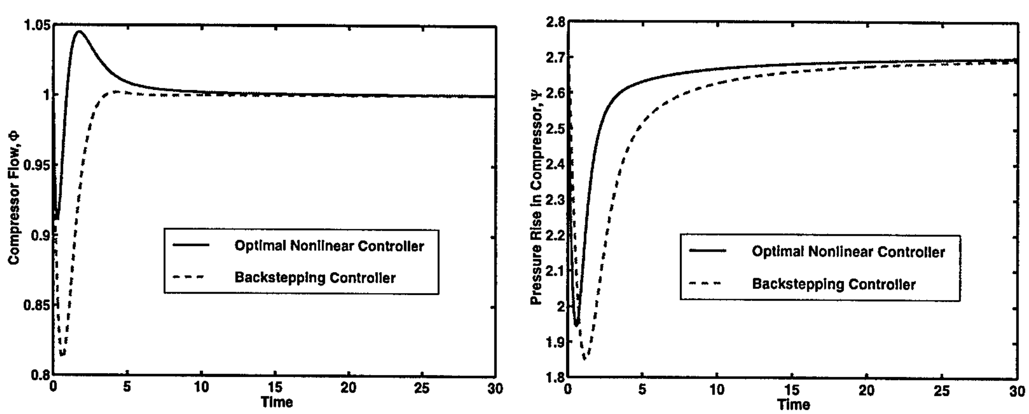


Figure 9: Compressor flow rate and pressure rise vs time

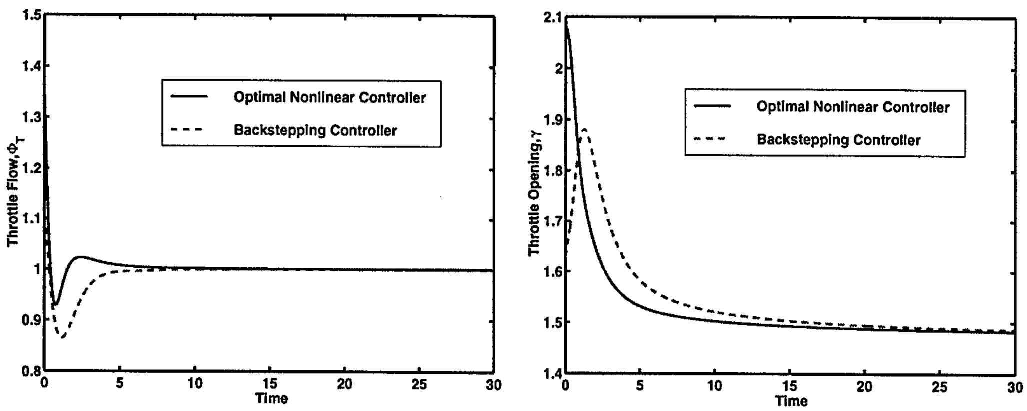


Figure 10: Control effort vs time

interacting subsystems, designing a controller that maximizes the net energy flow or, power, from the plant to the controller would generate disturbance rejection objectives. Within the context of linear H_∞ theory these ideas have been explored by matching the mechanical impedance of the plant to the impedance of the controller.

In [I.13] we develop a nonlinear controller synthesis framework that exploits the phenomenon of nonlinear dissipation. Such controllers can significantly enhance energy flow between plant and controller by introducing nonlinearities that induce broad-band spectral properties in the controller. In particular, for control of collocated flexible structures, if low frequency energy is injected into the structural system it can be dispersed to higher frequency bands by virtue of the coupling among the vibrational modes of the structure. This energy will be transferred to high frequencies and hence dissipated into heat through natural structural damping and the nonlinear dissipative controller. Hence, the nonlinear broad-band spectrum can be viewed as an effective energy transfer mechanism.

Since a linear/nonlinear structure has the ability to dissipate energy by its inherent damping associated with its vibrational modes, a purposefully designed nonlinear controller would create higher frequency harmonics and effectively transfer low-frequency disturbances to high frequency bands and hence maximize structural dissipation. Furthermore, the nonlinear dynamics within the compensator would induce a broadband spectrum which would enhance impedance matching between the plant and the compensator and, as a consequence, maximize energy transfer between the two subsystems.

2.30 Robust Controller Synthesis for Systems with Input-Output Nonlinearities: A Tradeoff Between Gain Variation and Parametric Uncertainty

In this research [I.5, I.15] a feedback control-design problem involving input-output nonlinearities and structured plant parameter uncertainties is considered. Multivariable absolute stability theory is merged with the guaranteed cost control approach to robust stability and performance to obtain a theory of full- and reduced-order robust control design that accounts for input-output time-varying sector bounded nonlinearities. The principal result is a sufficient condition for characterizing dynamic controllers of a fixed dimension which are guaranteed to provide robust stability for plant parametric variations and absolute stabilization for input nonlinearities. The proposed framework provides for a systematic design tradeoff between classical robustness guarantees (i.e., gain and phase margins) versus parametric robustness. Furthermore, the framework is directly applicable to uncertain systems with saturating controls and provides fixed-order dynamic output feedback controllers with a guaranteed domain of attraction.

2.31 State Space Modeling and Robust Reduced-Order Control of Combustion Instabilities

Thermoacoustic instabilities in combustion processes can have adverse effects on jet engine propulsion system performance. In this research [I.33, II.16, II.21] we formulate the problem of active control of combustion instabilities in a form that lends itself to the application of robust feedback control design. Specifically, a self-contained first principles derivation of the dynamic governing equations for combustion instabilities that is accessible to control-system designers requiring state space models for modern robust feedback control design is developed. Using the uncertain state-space system model the parameter-dependent Lyapunov function framework for robust fixed-order controller design is used to design high performance reduced-order robust controllers for suppressing thermoacoustic oscillations in combustion chambers.

2.32 An Implicit Small Gain Condition and an Upper Bound for the Structured Singular Value

The classical small gain theorem, along with its multivariable extension, provides the essential foundation for modern robust control theory. The extension of the small gain theorem in terms of the structured singular value provides reduced conservatism in the case of block-structured uncertainty. Whereas the small gain theorem provides necessary and sufficient conditions for robust stability in the presence of complex, frequency-dependent uncertainty, the robustness problem is considerably more difficult in the case of real uncertainty. Although the problem is NP-hard and ill posed, considerable effort has been devoted to obtaining tractable upper bounds. In [II.13] we develop a novel upper bound for the real structured singular value that has the form of an implicit small gain theorem. The implicit small gain condition involves a shifted plant whose dynamics depend upon the uncertain set bound and, unlike prior bounds, does not require frequency-dependent scales or multipliers. Numerical results show that the implicit small gain bound compares favorably with real-μ bounds.

2.33 Robust Fixed-Structure Controller Synthesis Using the Implicit Small Gain Bound

In this work [I.43, II.10] we explore the applicability of the implicit small gain guaranteed cost bound for controller synthesis. For flexibility in controller synthesis, we adopt the approach of fixed-structure controller design which allows consideration of arbitrary controller structures, including order, internal structure, and decentralization. Several numerical examples that have been addressed by means of alternative guaranteed cost bounds are presented to demonstrate the fixed-structure/implicit small gain approach to robust controller synthesis. Specifically, a quasi-Newton optimization algorithm was used to obtain robust controllers for structural systems with modal frequency and stiffness uncertainty. Figure 11 shows robust performance versus robust stability in the damped natural frequency of a two-mode flexible structure. The performance/robustness tradeoffs of the implicit small gain controllers are comparable to those of the scaled Popov controllers which are obtained using frequency-dependent multipliers.

2.34 Robust Controller Synthesis via Shifted Parameter-Dependent Quadratic Cost Bounds

One of the principal objectives of robust control theory is to synthesize feedback controllers with *a priori* guarantees of robust stability and performance. In structured singular value synthesis these guarantees are achieved by means of bounds involving frequency-dependent scales and multipliers which account for the structure of the uncertainty as well as its real or complex nature. An alternative robustness approach involves bounding the effect of real or complex uncertain parameters on the H_2 performance of the closed-loop system. These guaranteed cost bounds take the form of modifications to the usual Lyapunov equation to provide bounds for robust stability and performance.

In this research [I.17, II.8] parameterized Lyapunov bounds and shifted quadratic guaranteed cost bounds are merged to develop shifted parameter-dependent quadratic cost bounds for robust stability and robust performance. Robust fixed-order (i.e., full- and reduced-order) controllers are developed based on new shifted parameter-dependent bounding functions. The bound we construct is the most general of its kind developed thus far, encompassing the Popov, positive real, and shifted positive real bounds as special cases. The benefits of this generalization are demonstrated by numerical examples involving robust controller synthesis for flexible structures.

2.35 Structured Matrix Norms for Real and Complex Block-Structured Uncertainty

In this research [I.4, I.24] new upper and lower bounds for robust stability are developed for block-structured real and complex uncertainty involving arbitrary spatial norms. Specifically, norm-bounded, block-structured uncertainty is considered wherein the defining norm is not necessarily the maximum singular value. In the case where the defining norm on the uncertainty characterization is set to the spectral norm, the resulting upper bounds generalize upper bounds for

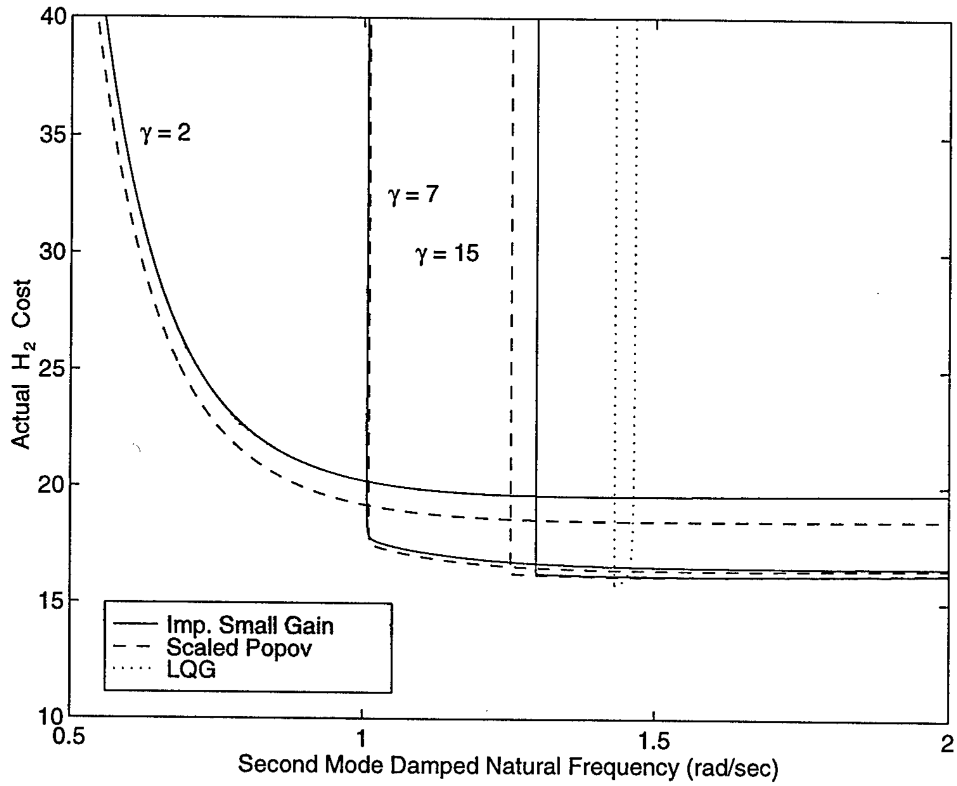


Figure 11: These plots of performance versus robustness in the second mode damped natural frequency illustrate the nonconservatism of the implicit small gain cost bound in comparison to LQG

mixed-μ by permitting the treatment of nondiagonal real uncertain blocks as well as accounting for internal matrix structure in the uncertainty.

2.36 Probability-One Homotopy Algorithms for Robust Controller Analysis and Synthesis with Fixed-Structure Multipliers

To enable the development of *M-K* (i.e., multiplier-controller) iteration schemes that do not require (suboptimal) curve fitting, mixed structured singular value analysis tests that allow the structure of the multipliers to *a priori* be specified, have been developed. These tests have recently been formulated as linear matrix inequality (LMI) feasibility problems. The least conservative of these tests always results in unstable multipliers and hence requires a stable co-prime factorization of the multiplier before the control synthesis phase of the *M-K* iteration. In this work [I.1] we first review the LMI formulation to robustness analysis. Then we develop alternative formulations that directly synthesize the stable factorizations and are based on the existence of positive define solutions to certain Riccati equations. These problems, unlike the LMI problems, are not convex. The feasibility problem is approached by posing an associated optimization problem that cannot be solved using standard descent methods. Hence, we develop probability-one homotopy algorithms to find a solution. These results provide computationally tractable algorithms for fixed-architecture, robust control design, which appear to have some advantages over the bilinear matrix inequality (BMI) approaches resulting form extensions of the LMI framework for robustness analysis.

2.37 A Riccati Equation Approach for Mixed H_2/L_1 Controller Synthesis

One of the fundamental problems in feedback control design is the ability of the control system to reject uncertain exogenous disturbances. Since a single performance objective is seldom adequate to capture multiple and often conflicting system disturbances, in this work [I.23, II.24] we develop a Riccati equation approach for mixed H_2/L_1 output feedback regulation. This multiobjective problem is treated by forming a convex combination of both H_2 (quadratic) and L_1 (worst-case peak amplitude response) performance measures. The principal result is a sufficient condition for characterizing static and fixed-order dynamic output feedback controllers involving a system of modified Riccati equations for optimizing H_2 performance within L_1 control design. We demonstrate the effectiveness of the proposed mixed H_2/L_1 Riccati equation approach via several design examples including command following for a high-performance fighter aircraft.

2.38 Stabilization of Linear and Nonlinear Systems with Time Delay

In dynamical systems such as the control of flexible structures with non-collocated sensors and actuators, teleoperators, biological systems, and electrical networks, time delay arises frequently and can severely degrade closed-loop system performance and in some cases drive the system to instability. Since controllers designed with the assumption of instantaneous information and power transfer may fail to stabilize dynamic systems with time delay it is of paramount importance that delay system dynamics be accounted for in the control-system design process. This work [I.9, II.19] considers the problem of stabilizing linear and nonlinear continuous-time systems with state and measurement delay. For linear systems we address stabilization via fixed-order dynamic output feedback compensators and present sufficient conditions for stabilization involving a system of modified Riccati equations. For nonlinear systems we provide sufficient conditions for the design of static full-state feedback stabilizing controllers. The controllers are delay-independent and hence apply to systems with infinite delay.

2.39 Optimally Tuned Passive Isolators and Absorbers using System Theoretic Performance Measures

In many practical applications unbalanced rotating machinery cause vibrations that transmit large oscillatory forces to the system foundation. Using *ad hoc* optimization schemes tuned isolators and absorbers have traditionally been designed to suppress system vibration levels by attempting to minimize the peak frequency response of the force/displacement transmissibility system transfer function. In this research [I.19, II.15] we formulate the classical isolator and absorber vibration suppression problems in terms of modern system theoretic criteria involving H_2 (shock response), mixed H_2/H_∞ (peak frequency response), and mixed H_2/L_1 (worst-case amplitude response) performance measures. In particular, using a quasi-Newton optimization algorithm we design H_2, mixed H_2/H_∞, and mixed H_2/L_1 optimally tuned isolators and absorbers for multi-degree of freedom vibrational systems. Finally, we compare out results to the classical Snowdon and Den Hartog absorbers.

2.40 Computational Algorithm Development

In collaboration with D. S. Bernstein at the University of Michigan, we are developing a *Robust Fixed-Structure Control Toolbox* integrated within the MATLAB environment that can be used to synthesize fixed-structure controllers that are optimal with respect to given performance measures, and at the same time satisfy stability and robustness constraints. The *Robust Fixed-Structure Control Toolbox* will focus on the development of a control design algorithm which supports the following paradigm: Minimize control law complexity subject to the achievement of a specified accuracy in the face of a specified level of uncertainty. This toolbox will be capable of handling a large class of problems, including decentralized compensation, constrained-structure compensation, controller design for multiple plant configurations, and mixed real and complex system uncertainty. The utility of this toolbox will facilitate implementation issues such as operational/physical constraints, operating-point variations, and processor throughput/memory limitations. Using the *Robust Fixed-Structure Toolbox* several fixed-structure controllers were designed for the ACTEX flight experiment [II.55].

3.0 Research Personnel Supported

Faculty

Wassim M. Haddad, Principal Investigator

Graduate Students

Rohit Kumar, M.S.

Weikun Wu, Ph. D.

JinHyoung Oh, Ph. D.

Several other students were involved in research projects that were closely related to this program. Although none of these students were financially supported by this program, their research did directly contribute to the overall research effort. Furthermore, three Ph. D. dissertations were completed under partial support of this program; namely

V. Kapila, *Robust Fixed-Structure Control of Uncertain Systems with Input-Output Nonlinearities,* Ph. D. Dissertation, School of Aerospace Engineering, Georgia Institute of Technology, Altanta, GA, November 1995;

V. Chellaboina, *Robust Stability and Performance for Linear and Nonlinear Uncertain Systems with Structured Uncertainty,* Ph. D. Dissertation, School of Aerospace Engineering, Georgia Institute of Technology, Altanta, GA, November 1996;

J.L. Fausz, *Robust Nonlinear Controller Synthesis for Nonlinear Dynamical Systems,* Ph. D. Dissertation, School of Aerospace Engineering, Georgia Institute of Technology, Altanta, GA, December 1997.

The first of the Ph. D. students, Dr. Kapila, holds the rank of Assistant Professor of Mechanical and Aerospace Engineering at the Polytechnic University, while the second of the Ph. D. students, Dr. Chellaboina, holds the rank of Assistant Professor of Mechanical and Aerospace Engineering at the University of Missouri. The third of the Ph. D. students, Dr. Fausz, is presently with the U.S. Air Force Research Laboratory at Kirkland AFB.

4.0 Interactions and Transitions

4.1 Participation and Presentations

The following conferences were attended over the past three years:

IFAC World Congress, San Francisco, CA, July 1996.
World Congress of Nonlinear Analysis, Athens, Greece, July 1996.
Circuit, Systems, and Computers, Athens, Greece, July 1996.
IEEE Conference on Control Applications, Dearborn, MI, September 1996.
American Control Conference, Albuquerque, NM, June, 1997.
IEEE Conference on Control Applications, Hartford, CT, September 1997.
IEEE Conference on Decision and Control, San Diego, CA, December 1997.
American Control Conference, Philadelphia, PA, June 1998.
IEEE Conference on Decision and Control, Tampa, FL, December 1998.
American Control Conference, San Diego, CA, June 1999.

Furthermore, conference articles II.1-II.55 were presented.

4.2 Transitions

To transition our theoretical developments to practical applications we applied our results to combustion and propulsion control. Specifically, our robustness results were applied to combustion systems to suppress the effects of themoacoustic instabilities as well as propulsion systems to control aerodynamic instabilities involving rotating stall and surge in jet engines. The controls combustion/propulsion laboratories headed by B. T. Zinn at Georgia Tech have been made available for controls studies in support of this program. These experimental testbeds provide the greatest potential for transitioning from theoretical developments to practical application. Recent analytical work supported by this program was communicated to Drs. C. A. Jacobson and A. Banaszuk of United Technologies, Hartford, Connecticut. Furthermore, the Principal Investigator's work was recently presented at GE Corporate Research and Development, Schenectady, New York, and United Technologies Research Center, Hartford, Connecticut.

5.0 Research Publications

5.1 Journal Articles

I.1. E.G. Collins, Jr., W.M. Haddad, L.T. Watson, and D. Sadhukhan, "Probability-One Homotopy Algorithms for Robust Controller Synthesis with Fixed-Structure Multipliers," *Int J. Robust and Nonlinear Control*, Vol. 7, pp. 165-185, 1997.

I.2. W.M. Haddad, "Correction to 'Absolute Stability Criteria for Multiple Slope-Restricted Monotonic Nonlinearities'," *IEEE Trans. Autom. Contr.*, Vol. 42, p. 591, 1997.

I.3. W.M. Haddad and V.-S. Chellaboina, "Robust Nonlinear-Nonquadratic Feedback Control via Parameter-Dependent Lyapunov Functions," *Int. J. Contr.*, Vol. 66, pp. 843-861, 1997.

I.4. V.-S. Chellaboina and W.M. Haddad, "Structured Matrix Norms for Real and Complex Block-Structured Uncertainty," *Automatica*, Vol. 33, pp. 995-997, 1997.

I.5. W.M. Haddad and V. Kapila, "Fixed-Architecture Controller Synthesis for Systems with Input-Output Time-Varying Nonlinearities," *Int. J. Robust and Nonlinear Control*, Vol. 7, pp. 675-710, 1997.

I.6. D.E. Williams and W.M. Haddad, "Active Control to Improve Vehicle Ride and Handling," *Vehicle System Dynamics*, Vol. 28, pp. 1-24, 1997.

I.7. D.C. Hyland, E.G. Collins, Jr., W.M. Haddad, and D.L. Hunter, "Neural Network System Identification for Improved Noise Rejection," *Int. J. Contr.*, Vol. 68, pp. 233-258, 1997.

I.8. W.M. Haddad, V. Kapila, and V.-S. Chellaboina, "Guaranteed Domains of Attraction for Multivariable Luré Systems via Open Lyapunov Surfaces," *Int. J. Robust and Nonlinear Control*, Vol. 7, pp. 935-949, 1997.

I.9 W.M. Haddad, V. Kapila, and C.T. Abdallah, "Stabilization of Linear and Nonlinear Systems with Time Delay," in *Stability and Control of Time-Delay Systems*, L. Dugard and E. Verriest, Eds., Springer-Verlag, pp. 205-217, 1997.

I.10. V.-S. Chellaboina and W.M. Haddad, "Solution to 'Some Matrix Integral Identities'," *SIAM Review*, Vol. 39, pp. 763-765, 1997.

I.11. W.M. Haddad, V.-S. Chellaboina, and J.L. Fausz, "Optimal Nonlinear Disturbance Rejection Control for Nonlinear Cascade Systems," *Int. J. Contr.*, Vol. 68, pp. 997-1018, 1997.

I.12. W.M. Haddad and V. Kapila, "Static Output Feedback Controllers for Continuous-Time and Discrete-Time Systems with Input Nonlinearities," *Eur. J. Contr.*, Vol. 4, pp. 22-31, 1998.

I.13. W.M. Haddad and V.-S. Chellaboina, "Nonlinear Fixed-Order Dynamic Compensation for Passive Systems," *Int. J. Robust and Nonlinear Control,* Vol. 8, pp. 349-365, 1998.

I.14. W.M. Haddad, V.-S. Chellaboina, J.L. Fausz, and C.T. Abdallah, "Optimal Discrete-Time Control for Nonlinear Cascade Systems," *J. Franklin Inst.,* Vol. 335B, pp. 827-839, 1998.

I.15. W.M. Haddad and V. Kapila, "Robust Controller Synthesis for Systems with Input Nonlinearities: A Trade-off Between Gain Variation and Parametric Uncertainty," *Int. J. Robust and Nonlinear Control.*, Vol. 8, pp. 567-583, 1998.

I.16. W.M. Haddad and V. Kapila, "Robust Stabilization for Continuous-Time Systems with Slowly Time-Varying Uncertain Real Parameters," *IEEE Trans. Autom. Contr.,* Vol. 43, pp. 987-992, 1998.

I.17. V. Kapila, W.M. Haddad, R.S. Erwin, and D.S. Bernstein, "Robust Controller Synthesis via Shifted Parameter-Dependent Quadratic Cost Bounds," *IEEE Trans. Autom. Contr.*, Vol. 43, pp. 1003-1007, 1998.

I.18. W.M. Haddad, V.-S. Chellaboina, and J.L. Fausz, "Robust Nonlinear Feedback Control for Uncertain Linear Systems with Nonquadratic Performance Criteria," *Syst. Contr. Lett.,* Vol. 33, pp. 327-338, 1998.

I.19. W.M. Haddad and A. Razavi, "H_2, Mixed H_2/H_∞ and H_2/L_1 Optimally Tuned Passive Isolators and Absorbers," *ASME J. Dyn. Sys. Meas. Contr.*, Vol. 120, pp. 282-287, 1998.

I.20. V. Kapila and W.M. Haddad, "Memoryless H_∞ Controllers for Discrete-Time Systems with Time Delay," *Automatica,* Vol. 34, pp. 1141-1144, 1998.

I.21. W.M. Haddad and V.-S. Chellaboina, "Optimal Nonlinear-Nonquadratic Feedback Control with L_2 and L_∞ Disturbances," *Nonlinear Analysis: Theory, Methods, and Applications,* Vol. 34, pp. 229-255, 1998.

I.22. W.M. Haddad, J. Fausz, V.-S. Chellaboina, and C. T. Abdallah, "A Unification Between Nonlinear-Nonquadratic Optimal Control and Integrator Backstepping," *Int. J. Robust and Nonlinear Control*, Vol. 8, pp. 879-906, 1998.

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